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VARIATION OF WIND VELOCITY AND GUSTS WITH HEIGHT

By R. H. Sherlock, M. ASCE

STRUCTURAL DIVISION

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Technical Division	*Proceedings-Separate Number*
Air Transport	42, 43, 48, 52, 60, 93, 94, 95, 100, 103, 104, 108, 121 (Discussion: D-XXVIII, D-7, D-16, D-18, D-23, D-43)
City Planning	58, 60, 62, 64, 93, 94, 99, 101, 104, 105, 115 (Discussion: D-16, D-23, D-43, D-60, D-62, D-65)
Construction	43, 50, 55, 71, 92, 94, 103, 108, 109, 113, 117, 121, 126 (Discussion: D-3, D-8, D-17, D-23, D-36, D-40, D-71)
Engineering Mechanics	41, 49, 51, 54, 56, 59, 61, 88, 89, 96, 116, 122, 124, 125, 126 (Discussion: D-5, D-XXIII, D-XXV, D-18, D-24, D-33, D-34 D-49, D-54, D-61)
Highway	43, 44, 48, 58, 70, 100, 105, 108, 113, 120, 121 (Discussion: D-XXVIII, D-7, D-13, D-16, D-23, D-60)
Hydraulics	50, 55, 56, 57, 70, 71, 78, 79, 80, 83, 86, 92, 96, 106, 107, 110, 111, 112, 113, 116, 120, 123 (Discussion: D-XXVII, D-9, D-11, D-19, D-28, D-29, D-56, D-70, D-71)
Irrigation and Drainage	46, 47, 48, 55, 56, 57, 67, 70, 71, 87, 88, 90, 91, 96, 97, 98, 99, 102, 106, 109, 110, 111, 112, 114, 117, 118, 120 (Discussion: D-XXIII, D-3, D-7, D-11, D-17, D-19, D-25-K, D-29, D-30, D-38, D-40, D-44, D-47, D-57, D 70, D-71)
Power	48, 55, 56, 69, 71, 88, 96, 103, 106, 109, 110, 117, 118, 120 (Discussion: D-XXIII, D-2, D-3, D-7, D-11, D-17, D-19, D-25-K, D-30, D-38, D-40, D-44, D-70, D-71)
Sanitary Engineering	55, 56, 87, 91, 96, 106, 111, 118 (Discussion: D-10, D-29, D-37, D-56, D-60, D-70)
Soil Mechanics and Foundations	43, 44, 48, 94, 102, 103, 106, 108, 109, 115 (Discussion: D-4, D-XXVIII, D-7, D-43, D-44, D-56)
Structural	42, 49, 51, 53, 54, 59, 61, 66, 89, 100, 103, 109, 113, 116, 117, 119, 121, 122, 123, 124, 125, 126 (Discussion: D-3, D-5, D-8, D-13, D-16, D-17, D-21, D-23, D-24, D-25-K, D-32, D-33, D-34, D-37, D-39, D-42, D-49, D-51, D-53, D-54, D-59, D-61, D-72)
Surveying and Mapping	50, 52, 55, 60, 63, 65, 68, 121 (Discussion: D-60, D-65)
Waterways	41, 44, 45, 50, 56, 57, 70, 71, 96, 107, 112, 113, 115, 120, 123 (Discussion: D-8, D-9, D-19, D-27, D-28, D-56, D-70, D-71)

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PAPERS

VARIATION OF WIND VELOCITY AND GUSTS WITH HEIGHT

By R. H. Sherlock,[1] M. ASCE

Synopsis

The flow of air in level, open country is adopted as the standard of reference in this paper, assuming that the influence of local shielding and unusual topography will be evaluated by the designer in each individual case, perhaps with suggestions in the code. Recommendations are based on velocity pressures rather than on design pressures.

The theory of the variation of wind velocity with height, based on the Ekman spiral, is first discussed. The records of a particular storm are used to validate the theory and to provide detailed information regarding gust characteristics. The duration and extent of the minimum effective gust is discussed. A recommendation is made for the variation of velocity pressure with height, to be used in obtaining the design pressure at any height. The magnitude of the design pressure will depend upon the recommended velocity pressure near the ground in each particular geographical location. A special recommendation is made for the case of guyed towers.

The one-seventh-power law is a sufficiently close approximation to the variation of 5-min wind velocity with height up to 1000 ft above which a constant velocity is justified. Gust factors are proportional to the inverse ratio of heights raised to the power 0.0625. The combined effect gives velocity pressures which are proportional to the ratio of heights raised to the power 0.161.

Introduction

The theory of the variation of wind velocity with height is discussed in the first part of this paper. Throughout the remainder of the paper the records of

Note.—Written comments are invited for publication; the last discussion should be submitted by **October 1, 1952**.

[1] Prof. of Civ. Eng., Univ. of Michigan, Ann Arbor, Mich.

a particular storm are used to validate the theory further and to provide detailed information regarding gust characteristics. The duration and extent of the minimum effective gust is also discussed. A recommendation is made for the variation of velocity pressure with height to be used in obtaining the design pressure at any height. The magnitude of the design pressure will depend upon the recommended velocity pressure near the ground in each particular geographical location. A special recommendation is made for the case of guyed towers.

The subject of the variation of wind velocity with height is complicated by the highly uncertain nature of much of the available storm observations and by the high cost of setting up a station to obtain this information under proper controls. The most voluminous information is contained in the reports of the Weather Bureau, Department of the Interior. These latter data, however, are not homogeneous since the condition under which they were taken varied from time to time. This variation is chiefly the result of the first-order stations having been located, until recently, in cities where the degree of exposure was constantly changing with the erection of new, tall buildings, and where the air flow was badly distorted by the buildings upon which the anemometers were mounted.

It is desirable that code recommendations be based on some standard of reference, such as air flow in level open country, and that the influence of local shielding and unusual topography be evaluated by the designer in each individual case, perhaps with suggestions in the code.

Definitions and Notations

The letter symbols introduced in this paper are defined where they first appear, in the text or by illustrations. Essentially, they conform to American Standard Letter Symbols for Structural Analysis (ASA-Z10.8—1949). Technical terms used in the paper are defined as follows:

Wind Velocity.—Speed and direction of air movements with reference to points on the ground. Units are in miles per hour unless otherwise noted.

Five-Minute Velocity.—Average velocity V_5, during five consecutive minutes. At a height of z feet above the ground, the 5-min velocity is designated V_z.

Gust.—Localized high wind velocity lasting a short time.

Gust Factor, F.—Gust velocity divided by the 5-min velocity. At a height of z feet above the ground, the gust factor is F_z.

Eddy.—A parcel of air with components of motion transverse to the general stream.

Eddy Viscosity.—Resistance to free laminar flow which is provided by eddies in the air stream.

Jet.—Temporary stream of air that moves at a higher velocity than the surrounding air.

Surface Wind.—Wind vector on the ground.

Gradient Wind.—Wind vector at a height at which the influence of the ground friction is negligible.

Geostrophic Wind.—A first approximation to the gradient wind, in which the inertia forces due to the curvature of the wind path are neglected.

Isobar.—Locus of points of equal atmospheric pressure, as shown on weather maps.

Pressure Gradients.—Rate of change of atmospheric pressure, as shown graphically by the spacing of the isobars on weather maps.

Gradient and Geostrophic Winds

There is some height at which the influence of the ground friction, transmitted upward through eddy-viscosity, has a negligible effect on the velocity of the wind as it responds to the pressure gradient. At this height the pressure gradient is said to be dynamically balanced against two components arising from centrifugal force, one due to the rotation of the earth and the other due to the curvature of the wind path. The wind velocity computed on this basis is called the "gradient wind." If the curvature of the wind path is neglected it is called the "geostrophic wind," which is sometimes referred to as the first approximation to the gradient wind.[2]

Theory of Wind Velocity Versus Height

The factors entering into the variation of wind velocity with height are the pressure gradient, the coefficient of eddy viscosity of the air, the mass density of the air ρ, the angular velocity of the earth's rotation, the geographic latitude at which observations are made, and the curvature of the wind path. This is on the usual assumption that the eddy viscosity does not change with the height due to different degrees of vertical mixing at different heights. The relation between these factors has been expressed by Horace Lamb[3] and G. I. Taylor.[4] The equations derived by Mr. Taylor have been discussed at length by W. Watters Pagon,[5] M. ASCE.

The equations developed by V. W. Ekman,[6] originally applied to ocean drift, may be used to construct a graphical representation of this relation. W. J. Humphreys[7] states the matter thus:

> "Ekman assumed a straightaway wind blowing over an initially quiet body of water of great extent and considerable depth, and found what would be the resulting movements of the water on the attainment of a steady state."

By inverting the system of coordinates, it is possible to find the resulting movements within a body of air relative to which the underlying water, or land, is apparently moving. It can be shown that the relation between wind velocity and height is represented graphically by an equiangular (logarithmic) spiral, if the velocity vectors are projected onto the surface plane, as shown in

[2] "Physical and Dynamical Meteorology," by D. Brunt, Cambridge Univ. Press, Cambridge, England, 1941, pp. 189–190.

[3] "Hydrodynamics," by Horace Lamb, 5th Ed., Cambridge Univ. Press, Cambridge, England, 1924, p. 655.

[4] "Eddy Motion in the Atmosphere," by G. I. Taylor, *Philosophical Transactions*, Royal Soc. of London, England, Series A, Vol. 215, 1915, p. 14.

[5] "Wind Velocity Variation with Height," by W. Watters Pagon, *Engineering News-Record*, Vol. 114, 1935, pp. 742–745.

[6] "On the Influence of the Earth's Rotation on Ocean Currents," by V. W. Ekman, *Arkiv för matematik, astronomi ocn fysik*, Stockholm, Sweden, 1905.

[7] "Physics of the Air," by W. J. Humphreys, 3rd Ed., McGraw-Hill Book Co., Inc., New York, N. Y., 1940, p. 128.

Fig. 1. In 1934, P. O. Huss, at the University of Michigan, Ann Arbor, Mich., found that this spiral also represents the relations as given by Messrs. Lamb and Taylor, since all three equations can be reduced to the same form.

In Fig. 1 the velocity of the surface wind is given in magnitude and direction by the vector AB; that of the gradient wind by AC; and that of the drift wind by their vectorial difference, BC. The velocity of the wind at any intermediate height z is given by the vector AD and the drift wind by DC. The angle

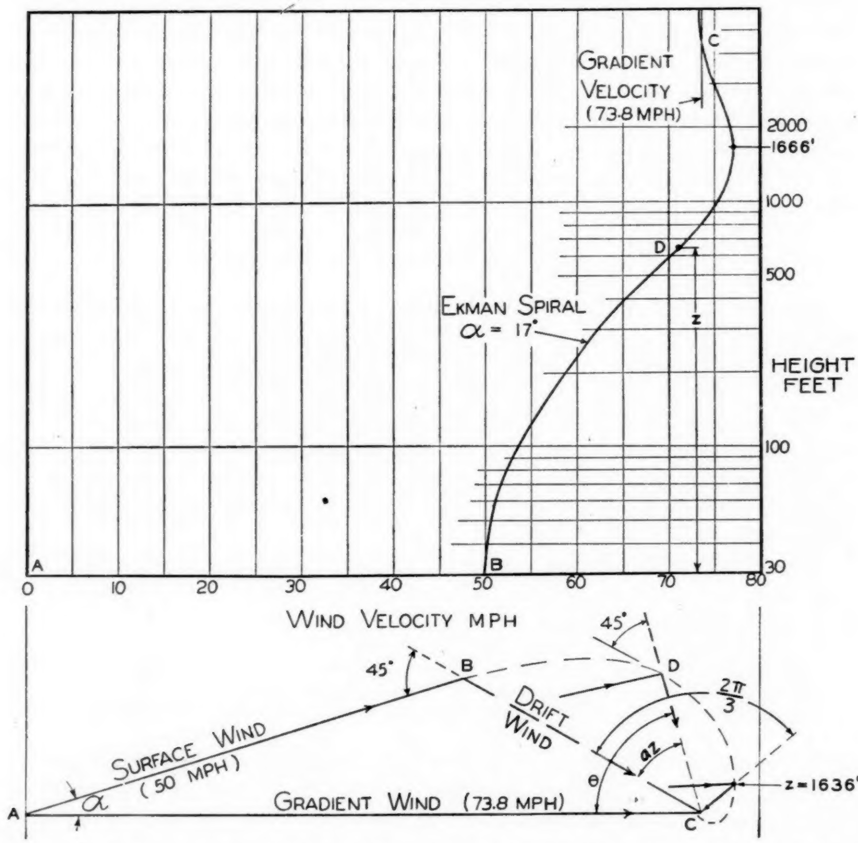

FIG. 1.—THEORETICAL VARIATION OF WIND VELOCITY WITH HEIGHT ACCORDING TO THE EKMAN SPIRAL

between the surface and drift winds is always 45° regardless of the value of α, the angle between the surface wind and the gradient wind. Since the vector AD gives the velocity at height z it is necessary to establish the point D on the spiral in order to obtain the velocity. The velocity may be obtained by letting $\theta = 45° - \alpha + a\,z$. There are then two unknown quantities, α and a. Mr. Humphreys makes use of the assumption that the wind velocity reaches a maximum at 500 m (1666 ft) and accordingly chooses the value $a\,z = \frac{2\pi}{3}$

at that height; whence $a = \frac{2\pi}{5000 \text{ ft}}$. There remains then the necessity of finding the value of α experimentally by observations during periods of strong winds.

In fitting the spiral to any set of experimental data it is necessary to choose (1) some point through which to pass the spiral at an assumed maximum value of the vector AD, as explained in the previous paragraph; and (2) an effective ground height as the value of $z = 0$ at point A, Fig. 1. The latter should be chosen at least high enough to escape the effects of small local units of roughness. The angle, α, of the spiral and its position are then chosen by trial to give the best fit to the observed points showing the relation between wind velocity and height, as in Fig. 2. The velocity at which the spiral reaches the gradient level is thus fixed automatically for each fitted spiral.

Observations during a winter storm will show that the direction of the gradient wind, as indicated by the direction of cloud movement, differs from the wind direction at the surface by a considerable angle, usually about 20° or less, but sometimes amounting to as much as 180° at the time of the wind-shift as a warm front or cold front is passing.

Storm Observations

The number of controlled experiments made for the purpose of studying the relation between wind velocity and height in open country has been very small, because of the great expense involved. On one such project[8] observations during winter wind storms were conducted over a period of seven years, and during the later phases of the project a steel tower 250 ft high was erected with a number of specially designed anemometers mounted on it. During some of the storms the spacing of the anemometers along the tower was 25 ft and the anemometers and recording oscillograph were adjusted for reading wind velocities for intervals as short as one-quarter second. The storm that was selected as being sufficiently representative to justify intensive study, and for which an unusually adequate amount of coincidental meteorological information was available, occurred on January 19, 1933. The experimental equipment for recording this storm has been reported elsewhere[9, 10, 11] together with some of the results.

Fig. 12, introduced subsequently, is a wind map showing the turbulent nature of the flow during a part of a typical run. The numbers at the bottom denote seconds, and it will be seen that this map includes a period of 39 sec; that is, seconds 210 to 249 of Run No. 026. The numbers within the map are the velocity readings in miles per hour, averaged over 0.25 sec at each station on the tower. The vertical distance between anemometer stations was either 25 ft or 50 ft. Iso-velocity contours were drawn so that a given contour line

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[8] "Storm Loading and Strength of Wood Pole Lines and Study of Wind Gusts," by R. H. Sherlock, M. B. Stout, W. G. Dow, J. S. Gault, and R. S. Swinton, Edison Electric Institute, 1936.

[9] "Wind Structure in Winter Storms," by R. H. Sherlock and M. B. Stout, *Journal of the Aeronautical Sciences*, Vol. 5, 1937, pp. 53–61.

[10] "The Relation Between Wind Velocity and Height During a Winter Storm," by R. H. Sherlock and M. B. Stout, *Proceedings*, Fifth International Cong. for Applied Mechanics, 1938, p. 436.

[11] "An Anemometer for a Study of Wind Gusts," by R. H. Sherlock and M. B. Stout, *Engineering Research Bulletin No. 20*, Univ. of Michigan, Ann Arbor, Mich., May, 1931.

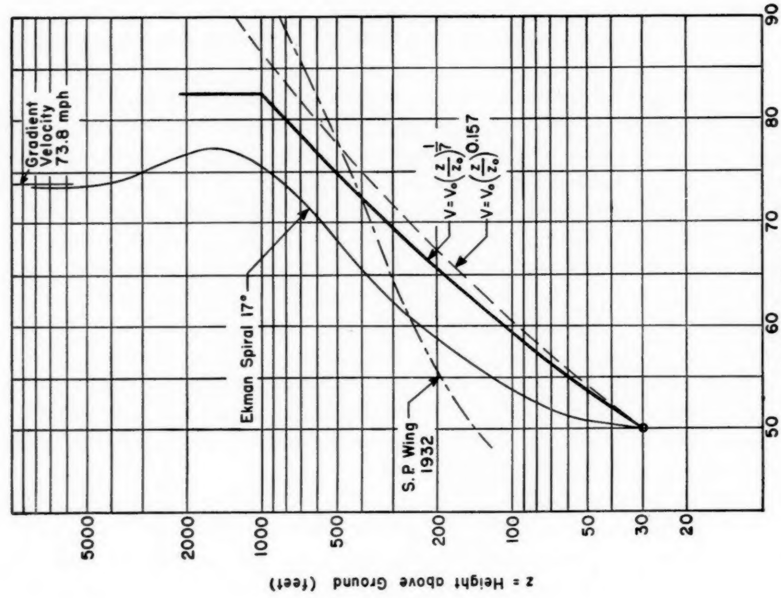

FIG. 3.—THREE CURVES COMPARED WITH AN EKMAN SPIRAL

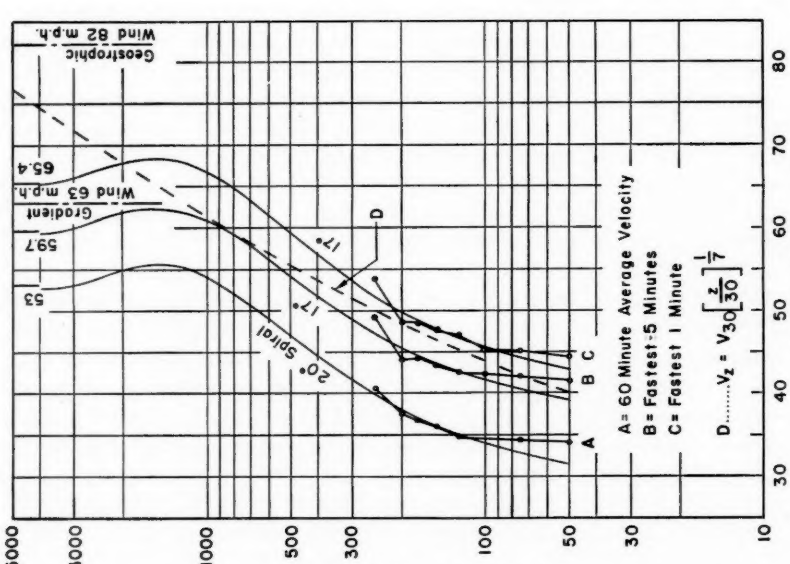

FIG. 2.—EKMAN SPIRALS FITTED TO OBSERVED WIND VELOCITIES AND COMPARED WITH COMPUTED GRADIENT WIND

always passes through the same velocity number. Where the contours are close together the velocity is changing rapidly.

In Fig. 2, three sets of data from this storm have been plotted. They show, respectively, the fastest one-minute velocity (Curve C), the fastest 5-min velocity (Curve B), and, finally, the fastest 60-min velocity (Curve A) within which the two shorter periods occurred. Also shown are the computed values of gradient wind and geostrophic wind.

Fortnuatley, the most intense part of the storm occurred about noon. At this time a large number of airports reported meteorological observations to the U. S. Weather Bureau. It was possible, therefore, to obtain these reports and to construct a weather map from which the pressure gradient and the curvature of the isobars could be determined. By assuming that the wind direction followed the isobars it was possible to compute the velocity of the gradient wind. There were then available two sets of independent observations, one being the variation of wind velocity with height as determined by measurements on the 250-ft tower, and the other being the computed coincidental gradient velocity. These were then used to test the validity of the Ekman spiral, and its associated theory, in representing actual conditions in the free-flowing air in fairly level, open country, during a wind storm.

The position and slope of the fitted spiral were determined primarily by those points on the tower which were above the influence of the ground topography. There was a slope of about 175 ft in $4\frac{1}{2}$ miles to the southwest, which is the direction from which the wind was blowing. This 4% slope to the windward side of the tower gave an increased velocity to the lower layers of the wind. The curves show that the ground effect extended approximately to the 100-ft level and that the velocities at the 50-ft and 75-ft levels were from 1 to $2\frac{1}{2}$ miles per hr higher than the fitted spiral.

At the two highest stations irregularities occurred in the 1-min and 5-min data. These have been shown[12] to depend upon temporary channels of high velocity which maintain themselves for 10 sec or 15 sec, and at times even for 1 min, and which tended to recur at the same height.

The five upper stations of the 60-min curve, however, deviated from the wind spiral by only a fraction of 1 mile per hr, whereas at the gradient level the fitted spiral was 10 miles per hr below the gradient level. It should be remembered that the pressure gradient may be changing at any given location, as the low-pressure area is passing; also, that there are local deviations not usually shown on the small-scale synoptic charts of the U. S. Weather Bureau. Therefore, it would not be surprising, if, over a period of 60 min, the average pressure gradient at this location should have changed so as to decrease the average gradient velocity from 63 to 53 miles per hr.

The fastest 1-min velocity occurred within two or three minutes of the noon hour at which the barometer readings were taken at the various airports. It would be expected that there would be better agreement between the fitted spiral and the gradient velocity for this 1 min than for the 60-min period, provided that it is assumed that the 1-min interval is a sufficiently long period of

[12] "Gust Factors for the Design of Buildings," by R. H. Sherlock, International Assn. for Bridge and Structural Eng. Publications, Zurich, Switzerland, Vol. 8, 1947, p. 209.

time for establishing compatible values between velocity and pressure gradients throughout the full depth of atmosphere below the gradient level. The average velocity within this depth was approximately 60 miles per hr and, therefore, this interval measured the passage of approximately one mile of wind. This mass of moving air, therefore, was between two and three times as long as it was deep. A closer agreement could have been obtained by giving greater weight to the five readings from 100 ft to 200 ft and less weight to the reading at 250 ft. This approach might have been justified on the grounds that the high velocity exhibited at the 250-ft level is the result of one or more of the transient "jets" previously referred to as "temporary channels." Such jets would have required a spiral of about 18° instead of 17°.

The deviations of the 5-min spiral are greater than those of the 1-min spiral. The points on the tower show less regularity, and if the same argument were used for underweighting the point at the 250-ft level, an 18° spiral could have been justified instead of the 17° spiral. This would have resulted in a still greater difference at the gradient level. However, it was felt that the points at the 200-ft and 250-ft levels should be given their full values in fitting the spiral, and this was done.

It has been seen that the computed gradient wind is about midway between the spirals for the fastest 5 min and the fastest 1 min, whereas the geostrophic wind is far faster than the fitted curves. This indicates that the curvature of the wind path, which was ignored in computing the geostrophic wind, contributed an important component to the dynamic balance. When it is considered that the curvature of the wind path was estimated from the curvature of the isobars, the fit between the spiral and the two sets of independent observations (anemometer readings and computed gradient wind) must be said to be very good indeed. The curvature of the isobars would normally be less than the curvature of the wind path and, therefore, the computed gradient wind is the lowest reasonable value. A higher value would give a better fit to the 17° curve for the fastest 1 min.

This is only one storm; but it is a typical storm, for which the coincidental meteorological characteristics[13] might well serve as textbook material illustrating severe storms in the United States. The conclusions which may be drawn from these observations are:

1. The theory expounded by Mr. Taylor[4] and others fits the experimental data for this fairly intense winter storm very well;

2. The angle between the surface wind and the gradient wind in such a storm will lie between 17° and 20° depending upon the period of time over which the velocity is averaged; and

3. The curvature of the wind path supplies an important component in establishing the gradient wind, amounting in this case, if ignored, to 30% of the gradient wind.

The Seventh-Power Law

In Fig. 2 a one-seventh power curve has been drawn so as to pass through the value of 40 miles per hr at the 50-ft level. This is a slightly higher velocity

[13] "Gust Factors for the Design of Buildings," by R. H. Sherlock, International Assn. for Bridge and Structural Eng. Publications, Zurich, Switzerland, Vol. 8, 1947, Fig. 3.

than that of the fitted curve for the fastest 5 min. The slope of the power curve between the 100-ft and 200-ft levels is remarkably similar to that of the fitted spirals. In general it gives only a small deviation from the fitted spiral below the 1000-ft level. The extent of the deviation will depend upon the level at which the power curve is started. If it were made to coincide with the spiral at the 100-ft level the deviations would be smaller than those shown in the diagram, whereas if it were made to coincide at the 30-ft level the deviations would be considerably increased. If it is desired to use a power curve as an approximation to the theoretical curve, it should be used only up to about the 1000-ft or 1500-ft level above which a constant velocity should be used.

In Fig. 3 the 17° Ekman spiral has been repeated, but this time it has been passed through the point giving 50 miles per hr at a height of 30 ft, as was done in Fig. 1. This is a point sometimes used in discussing the U. S. Weather Bureau records for the fastest daily 5-min average velocity. The one-seventh power curve has been passed through this same point, and it is seen that by lowering this "effective ground level" the deviations between the spiral and the power curve have become greater than in Fig. 2. They amount to 7 miles per hr, or about 9% of the theoretical value, at the 1000-ft level.

In his discussions of the Taylor equations, Mr. Pagon[5] has used the power 0.157, as considered by Ludwig Prandtl and O. G. Tollmien, instead of 0.143 (=1/7). This curve is likewise shown, and is obviously more conservative.

U. S. Weather Bureau Data

Fig. 3 likewise shows a curve for the maximum 5-min velocity presented by S. P. Wing[14] in 1931. This curve is based on an outstanding analysis of the U. S. Weather Bureau records for Chicago, Ill., and New York, N. Y. Because of the badly dispersed nature of the records Mr. Wing considered it necessary to use statistical methods in his analysis. It is believed that his approach to an interpretation of these results was a proper one and that the only criticism that can be raised against the curve must be based on the changing conditions of exposure, the distorted pattern of flow around the buildings on which the anemometers were mounted, and the pessimistic prediction of what the wind may be expected to do above the highest elevation available in these records—454 ft. In this latter prediction Mr. Wing was influenced at least to some extent by statements attributed to W. H. Dines and C. F. Marvin, that the wind doubled at from 1000 ft to 1500 ft above the ground. The curves proposed by Mr. Wing for the variation of 5-min velocities with height must be looked upon as ultra-conservative, but as being probably the best available analysis of the Weather Bureau records as they bear upon the question of the variation of wind velocity with height.

Gust Factors

Before the wind pressures acting on a structure can be determined it is necessary to select the maximum wind velocity that is proper for the locality and for the size and exposure of the structure. This is the design velocity.

[14] "Wind-Bracing in Steel Buildings," Second Progress Report of Sub-Committee No. 31, Committee on Steel of the Structural Division; Discussion by S. P. Wing, *Proceedings*, ASCE, August, 1932, p. 1103.

It must include an allowance for gusts which are of relatively short duration but which are of sufficient extent to envelop the structure and to permit the resulting aerodynamic pressures to develop on all sides of the structure.

The Weather Bureau records contain very little on the subject of gusts since its reports are based on 5-min average velocities. The fastest mile of passing wind can be read from the records, but this is of only limited usefulness since, in a gale, it corresponds to a period of about 1 min during which several strong fluctuations may occur. Also, the fastest mile of wind is difficult to read accurately from the type of record used in the Weather Bureau. It is necessary to supplement the Weather Bureau records of 5-min average velocity, therefore, by studies of gustiness in records from other sources.

Gustiness is accompanied by so many variations of velocity, temperature, and humidity that no comprehensive theory exists as to why it arises or how it proceeds.[15] However, it may safely be assumed that gusts are caused chiefly by the growth of eddies, local pressure differences, deflection around objects, vertical thermodynamic interchange, and by combinations of these causes. The most important cause is unquestionably vertical interchange due to thermal instability. This phenomenon is well known and has been studied extensively.[16]

When a cold air mass moves over ground that has previously been covered by a warm air mass, or when a warm air mass is overrun by a cold air mass, the lower strata are warmed so that the conditions necessary for thermodynamic stability are altered. Usually, but not always, the highest velocities and the most violent gusts occur within the southwest quadrant of the low-pressure area, that is, while the highly turbulent and unstable front portion of the cold air mass is passing. In this zone of transition there is a condition of thermal instability which permits occasional and sometimes violent interchanges between the higher and lower strata. Large gusts occur near the ground because masses of air from the more rapidly moving higher strata reach the ground before losing all of their excess forward momentum. Gusts from this source may be of a violence limited only by the kinetic energy present in the high strata.

Near the ground the wind is unable to respond fully to the pressure-gradient because of friction. This retarding effect is transmitted upward through the medium of eddy-viscosity—that is, through the resistance to free laminar flow that is provided by the transverse components of motion in the eddies. However, there is some height at which the effect of ground friction is negligible, and where the air is free to respond to the pressure gradient without this retarding effect. As the warm air at the lower levels is forced upward by the heavier cold air it must be replaced by the colder, fast moving air from above. If the masses of air involved in this interchange are sufficiently large, the retardation produced upon the falling mass of air, through eddy viscosity and collision with slower moving masses, may be so small that the descending mass loses only a small part of its velocity before reaching the lower strata, and a violent gust occurs.

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[15] "Physical and Dynamical Meteorology," by D. Brunt, Cambridge Univ. Press, Cambridge, England, 1941, p. 212.

[16] "Weather Analysis and Forecasting," by S. Pettersen, McGraw-Hill Book Co., Inc., New York, N. Y., 1940, p. 11.

The vertical speed with which this increased velocity travels downward has been shown by the wind maps to have been about 40 ft per sec, that is, about 27 miles per hr[17] in one case, and about 14 ft per sec in another.[18] These observations were on the 250-ft tower. This effect could be produced through shear between horizontal layers or through vertical displacement, as described, or through a combination of these two means. At any rate this effect of increasing velocity through falling masses of rapidly moving air have been shown to reach the ground within a few seconds after first appearing at the 250-ft level; or, to descend to a level of 200 ft or 250 ft and then to recede without having reached the ground; or to have receded and then resumed the descent within 3 sec.[18]

The rate of change of wind velocity with height has been shown to be very great during periods of temperature inversions.[19] However, such inversions do not occur in conjunction with steep pressure-gradients and, consequently, with high gradient-velocities. During those storms when high velocities occur the vertical mixing is so active as to destroy any possibility of the stability required for temperature inversion. The inversions usually occur when a warm air mass moves over ground that has previously been covered by a cold air mass, or when a warm air mass overruns a cold air mass, and this creates a condition favorable to stability and unfavorable to the gustiness of vertical interchange.

Gust factors are referred to the 5-min average velocity in this paper because that is the principal unit used in the long-time records of the U. S. Weather Bureau. The gusts that occur within such a period may have any duration up to 5 min; that is, 300 sec. The gust factor, within any 5-min interval, is defined as the ratio of the fastest gust velocity to the 5-min average velocity. Within a storm there will be 5-min intervals of many different velocities and these will be distributed in accordance with some statistical law. That 5-min interval which has the highest velocity may be looked upon as a gust within the storm. Its average velocity will approach, and through deflections may actually exceed, that which could be expected from the spiral fitted to the computed gradient velocity. It is not to be expected, then, that the gust factors in the fastest 5-min interval for a given storm will be as great as within a 5-min interval of lesser velocity.

This phenomenon is shown in Fig. 4, which is taken from a report of gustiness during the same storm for which the characteristics of the Ekman spiral were previously discussed.[20] Each point is for a particular 5-min interval whose velocity is expressed in units equal to the average velocity of the storm sample. A Pearson Type III statistical curve was used to establish an envelope for each set of points. It appears that the gust factors that occurred within the storm were greatest for those 5-min intervals which had approximately the

[17] "Picturing the Structure of the Wind," by R. H. Sherlock and M. B. Stout, *Civil Engineering*, June, 1932, p. 361.

[18] "Wind Structure in Winter Storms," by R. H. Sherlock and M. B. Stout, *Journal of the Aeronautical Sciences*, Vol. 5, 1937, Fig. 10.

[19] "Wind Structure Near the Ground and its Relation to Temperature Gradient," by G. S. P. Heywood, *Quarterly Journal*, Royal Meteorological Soc., Vol. 57, 1931, p. 433.

[20] "Gust Factors for the Design of Buildings," by R. H. Sherlock, International Assn. for Bridge and Structural Eng. Publications, Zurich, Switzerland, Vol. 8, 1947, Fig. 15.

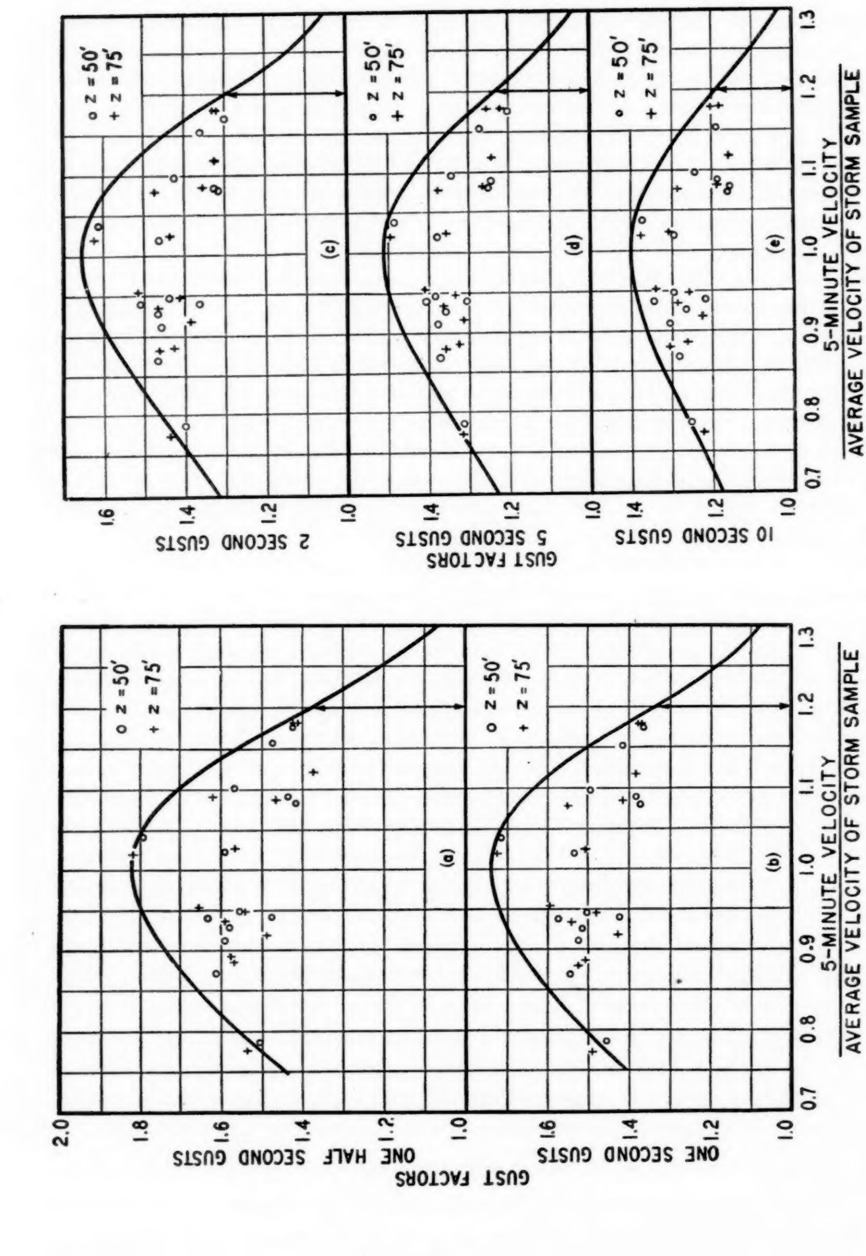


Fig. 4.—Envelopes for Observed Gust Factors of Various Gust Durations

average velocity of the storm, and were lowest for those 5-min intervals which approached the maximum for the storm. It is important to note that no 5-min velocity exceeded the storm average by more than 20%, and, as would be expected, that the gust factors were largest for the shortest gust period.

Fig. 5 illustrates a different method of showing the variation of gustiness with height. Here a total of fourteen 5-min intervals have been separated into three groups. Group 1 represents the average of six 5-min intervals for a total of 30 min. Groups 2 and 3 represent the averages of four 5-min intervals for a total of 20 min each.

Fig. 5(a) shows that Group 1 has the highest velocities, Group 2 intermediate velocities, and Group 3 the lowest velocities except at the 200-ft level. Fig. 5(b) shows the increments ΔV_5 that were added to the 5-min veloc-

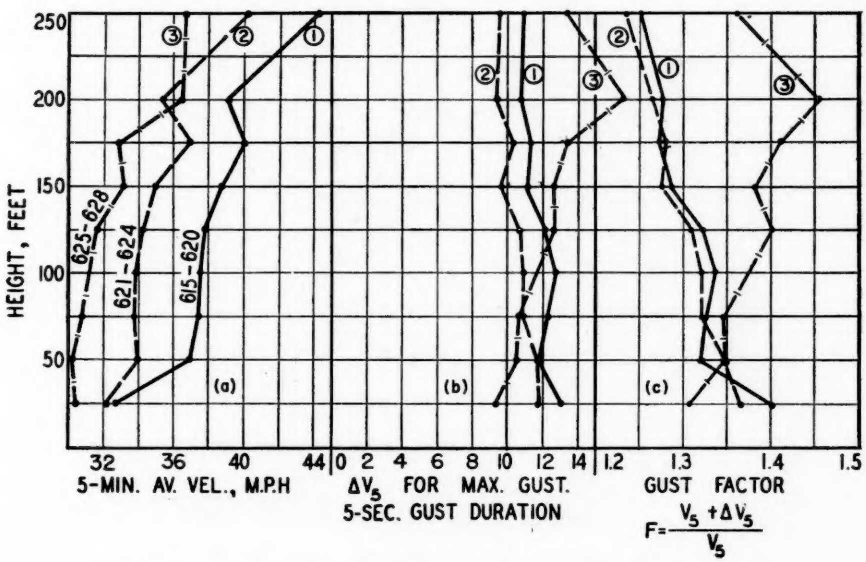


FIG. 5.—WIND VELOCITIES AND GUST FACTORS OBSERVED ON THE 250-FT TOWER

ities by the gusts of these three groups; 5-sec gusts are used for purpose of illustration. The maximum 5-sec gust was chosen for each 5-min interval and the average of all such gusts was taken for each group of intervals at each elevation. At the upper stations of the tower the largest gusts are those which occur with the lowest 5-min velocities, that is, in Group 3. In Fig. 5(*c*) are plotted the gust factors—

$$F = \frac{V_5 + \Delta V_5}{V_5} \qquad (1)$$

—for the same three groups, again computed for each 5-min interval and averaged for each group at each elevation. At all except the 25-ft elevation the largest gust factors accompany the lowest 5-min velocities.

The design velocity that must eventually be chosen will be equal, in each case, to a 5-min velocity multiplied by the proper gust factor. Therefore, the question must be answered:

"Will the lower five-minute velocities with high gust factors ever produce a higher design velocity than that which is obtained by taking the highest five-minute velocity on record and applying to it a lower gust factor?"

Before answering this question it should be noted that, for the higher V_5-velocities (in miles per hour), ΔV_5 decreases only slightly with height, whereas V_5 increases rapidly with height. This means that the decrease in gust factors with height, which has such an important part in later discussions, is due mostly

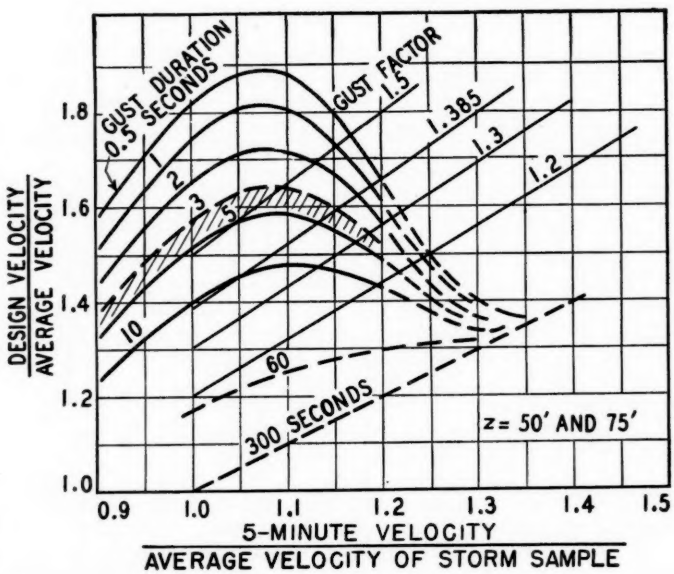


Fig. 6.—Nomogram Giving the Relation between 5-Min Velocity, Gust Factor, Gust Duration, and Design Velocity (z = 50 ft and 75 ft)

to the increasing values of V_5 rather than to the decreasing values of ΔV_5. There is a fundamental difference in interest, therefore, between the areonautical designer and the structural designer. To the former the magnitude of the gust in miles per hour is usually most important, and to the latter the most important consideration is its percentage of the steady wind to which it must be added.

In Fig. 6 the envelopes for the data in Fig. 4 have been replotted in such a way as to answer this question:

"Which gives the higher design velocity, a high 5-min velocity with a small gust factor or a low 5-min velocity with a large gust factor?"

Since the relation between the gust factor and the 5-min average velocity depends on the position of the 5-min interval within the storm, it was decided

to use the average velocity of the storm sample as the unit of velocity. In other words, the 5-min velocity is divided by the average of the storm sample to obtain the 5-min velocity in storm units. The design velocity is plotted vertically and the 5-min velocity horizontally. Here the curves have been shown as solid lines up to a value of 1.2 for the V_5-velocity, since no 5-min interval during this storm exhibited a higher velocity. Diagonal lines are drawn to show the relation between the V_5-velocity, the gust factor F, and the design velocity.

It is readily seen that the highest design velocity does not occur either at the storm average or at the peak when $V_5 = 1.2$, except in the case of large gusts having a duration of 60 sec. In this latter case $F = 1.08$ at $V_5 = 1.2$; but at the storm average, $F = 1.17$. The corresponding design velocities,

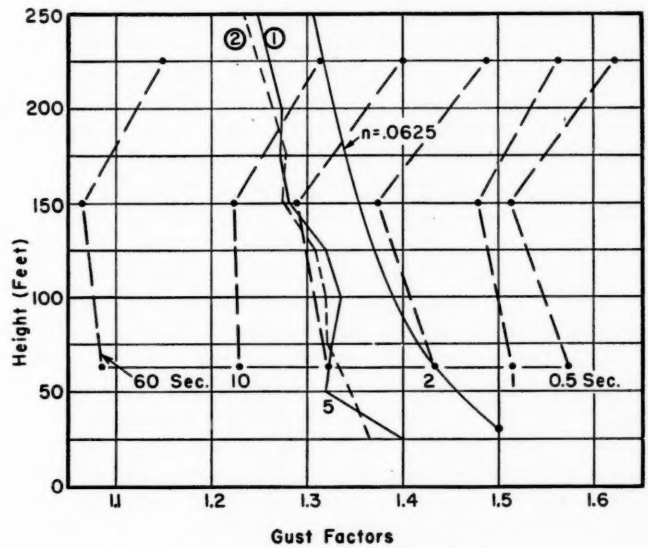


FIG. 7.—VARIATION OF GUST FACTORS WITH HEIGHT

expressed in units of the storm average, are 1.30 and 1.17, respectively. Obviously the larger design velocity will be obtained by using the highest V_5 (that is, $V_5/V_{aver} = 1.2$) with its accompanying lower gust factor in the case of 60-sec gusts. This is not always the case, however. For example, the curve for 10-sec gusts shows that the design velocity for maximum V_5 is 1.43 and for the storm average is 1.40, neither of which is the maximum. An intermediate value of V_5 gives the maximum design velocity of 1.475 with a gust factor of 1.34. The answer in this case, then, is that neither the average of the storm sample nor the maximum value of V_5 has an accompanying gust factor that gives the maximum design velocity. This condition is true for all curves shown here for gust durations of 10 sec or less.

Fig. 7 has been drawn to show the relation between gust factors and height for different gust durations from 0.5 sec to 60 sec. Dash lines are values

observed during the passage of a jet at the 225-ft level, and n is the exponent of a fitted curve. The points shown at elevation 62.5 ft are taken from Fig. 6 covering observations at 50 ft and 75 ft; those for elevation 150 ft are taken from a similar drawing covering observations at 125 ft, 150 ft, and 175 ft; and those shown at an elevation of 225 ft are from data for heights of 200 ft and 250 ft. Here the gust factors are obtained by dividing the highest design velocity by $V_5 = 1.2$ (in storm units) in order to obtain an adjusted gust factor. For example, at the elevation $z = 62.5$ ft, Fig. 6 shows that for a gust duration of 10 sec the maximum design velocity is 1.475. This occurs approximately at $V_5 = 1.1$ with a coincidental gust factor of 1.34; but the gust factor in Fig. 7 was obtained by dividing 1.475 by 1.2 instead of 1.1. This gave the adjusted gust factor of 1.23 shown in Fig. 7. This method was used for all other points in the diagram. In this manner the U. S. Weather Bureau records for the daily fastest 5-min velocity can be used in connection with gust factors that have been adjusted to give the highest design velocity in the storm. This method is valid on the assumption that the relationships shown in Fig. 6 for this storm are likewise representative of other severe storms.

The data for the observed 5-sec high velocity groups 1 and 2 shown in Fig. 5(c) have been replotted in Fig. 7 for the purpose of comparison. Below 150 ft the decrease of gust factor with height is practically the same in both cases. Also a smooth exponential curve has been drawn to pass through the two points $F = 1.5$ at El. 30 ft and $F = 1.15$ at El. 2000 ft. The slope of the curve is nearly the same as for the data taken from Fig. 5(c) and for the data below 150 ft in Fig. 7. However, at the upper stations the influence of the high values of the gust factors in lower V_5-intervals is such that the points exceed the fitted curve by a substantial amount. The reason for this variation is to be found partly in the existence of temporary jets as shown subsequently in Fig. 12, which demonstrates that there are jets lasting from Second No. 214 to 232 and from 237 to 245 during Run Number 026. These jets were probably generated by unbalanced pressures between two fairly large masses of air within the larger flowing mass. Such temporary channels have also been shown on a smaller scale in the observations of Wilhelm Schmidt.[21] It was he who first applied the expression "jets" to these phenomena.

Fig. 8 shows the variation of wind velocity with height during the passage of a jet at elevation 200 ft. A total of 30 sec is shown, divided into three periods of 10 sec each; thus (see Fig. 12, introduced subsequently):

Curve:	Shows the average of:
1	Seconds 214 to 224
2	Seconds 224 to 234
3	Seconds 236 to 246

This 32-sec period is coincident with the arrival of a gust that had been preceded by another gust whose effect had not yet disappeared entirely. The equation—

$$V \propto \left(\frac{z}{30}\right)^{0.161/2} \qquad \text{(2)}$$

[21] "Turbulence Near the Ground," by Wilhelm Schmidt, *Journal*, Royal Aeronautical Soc., London, England, May, 1935, p. 361.

—which is recommended for the variation of velocity with height, including a gust factor, is representated by the heavy solid line (Curve 4). It shows that the jet at the 200-ft station establishes a velocity curve that exceeds the actual velocity at the 250-ft elevation by 7.9%, and at the 175-ft elevation by 17.9%, of the expected velocities at these points.

Since small jets of less than 1 m have been observed near the ground by Mr. Schmidt, and larger jets of 50 ft to 75 ft, with 1-min duration, and at a height of 200 ft have been observed at the University of Michigan, it is only prudent to assume that the pressure differences that gave rise to these jets can

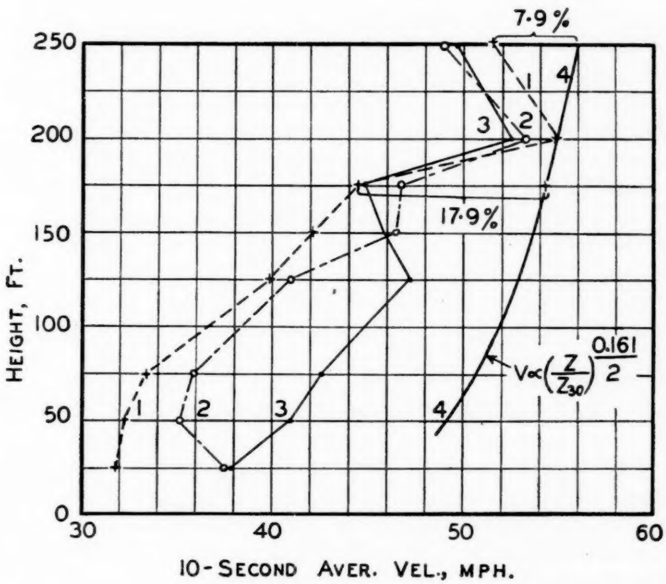


FIG. 8.—VARIATION OF WIND VELOCITY WITH HEIGHT DURING THE PASSAGE OF A JET

also exist in still larger sizes and at higher elevations. Some allowance must be made for them when fitting curves to data showing the decrease of gust factors with height.

Minimum Effective Gusts

A structure will not respond to the pressure of a gust that is only a small fraction of the size of the structure. The gust must have sufficient vertical and horizontal extent to envelop not only the structure but also those flow patterns to the windward and to the leeward which are responsible for the maximum pressures on the structure. In the case of a building, turbulence will be generated to the leeward involving a mass of air which is separated from the higher undisturbed flow by vortex layers. In front of the building, a turbulent zone is likewise formed, and it likewise is separated from the higher streamlined flow by a vortex layer. The entire flow pattern is such as to produce, within the air, a streamlined surface that offers a minimum loss of energy to the flow past the building. After the streamlined flow has been

established in the wind, there may be superimposed upon the average flow the additional velocities of a gust.

The size of the gust necessary to envelop a sufficient amount of this streamlined wind structure to transmit the corresponding changes in pressure to all sides of the building has been shown[22] to be about eight times the dimension of the building along the wind direction. This factor, eight, is based on a study of experiments[23] performed on airfoil sections. The results are adopted here because of the absence of experimental data based on sharp-edged structures, and because this procedure is believed to be conservative. Under this assumption, if a gust is traveling at 75 miles per hr it should have a duration of at least 3 sec in order to be fully effective in establishing new pressures on all the surfaces of a building whose dimension is about 40 ft along the stream.

The lateral extent of the gust must also be considered. It would need to be the length of the building plus some reasonable fraction of that length. For a small building about 50 ft across the wind stream, an allowance of half this length at each end would give a gust front about 100 ft wide. It has been shown[24] that when the gust factor is computed for such a width it will be from 3% to 8% less than if it had been computed from the records of an anemometer measuring velocities at a point.

In selecting the minimum effective gust it is necessary to make several assumptions, most of which are conservative, but some of which are not. It is believed that the balance is on the conservative side. They are as follows:

1. The results regarding the wake of a building, obtained by investigators on particular shapes of buildings, apply reasonably well to other shapes of structures;
2. The time lag in the development of the pressures on an airplane wing applies also to buildings and, therefore, a gust eight times the length of the building is adequate to develop the new pressures;
3. The lateral flow around the ends of buildings decreases the length of the wake and consequently the length of the minimum effective gust; but this adverse condition is more than offset by (*a*) the favorable margin in Item 2 and (*b*) the fact that the gust factor is later chosen on the basis of observations taken by an anemometer at a point, whereas, buildings are affected by gusts of considerable width with a consequent decrease in the gust factor; and
4. An additional margin of safety is later introduced in selecting the position of the fitted curve.

Fig. 9 shows an idealized diagram of the manner in which a large gust is generated by the descent of a mass of air from the gradient level. It has previously been mentioned that some gusts have been shown to descend with a velocity of 40 ft per sec (27 miles per hr). This descent is not uniform but is made in surges due to the unquestionably turbulent nature of the gust front.

[22] "Gust Factors for the Design of Buildings," by R. H. Sherlock, International Assn. for Bridge and Structural Eng. Publications, Zurich, Switzerland, Vol. 8, 1947, p. 221.

[23] Proceedings of the 3rd International Cong. for Applied Mechanics, Stockholm, Sweden, 1930, p. 329, Fig. 8.

[24] "Gust Factors for the Design of Buildings," by R. H. Sherlock, International Assn. for Bridge and Structural Eng. Publications, Zurich, Switzerland, Vol. 8, 1947, p. 220.

If it is desired to envelop the entire depth of a tall structure, such as a modern tower building, the gust would have to be of such duration that it would have proceeded at least six times the size of the building downwind from its windward face.

During the time that the minimum effective gust is being developed at the lower part of the building the gust at the top of a building 1000 ft high would have been blowing for considerably more than 30 sec. The probability that the entire height of such a tall building would be simultaneously subject to the maximum 10-sec gust is very remote. Therefore, if the 10-sec gust is taken for purpose of establishing the design velocity there would be a statistical margin of safety when applied to a very tall structure.

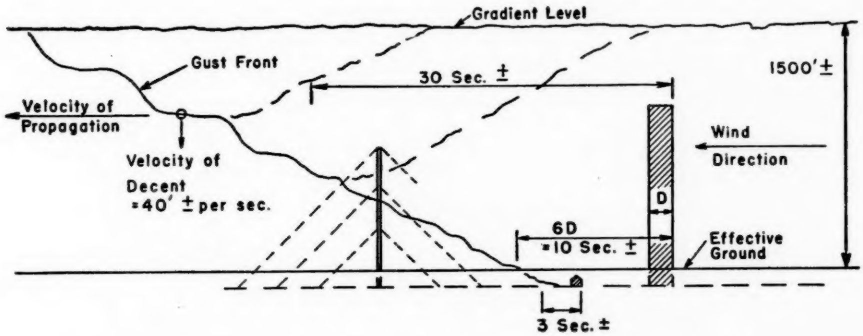


FIG. 9.—IDEALIZED PASSAGE OF A GUST PAST A HIGH BUILDING AND A GUYED TOWER

The 10-sec gust is hereby adopted for the purpose of this paper, and the corresponding gust factor is taken at $F = 1.5$ for an elevation of 30 ft and at $F = 1.15$ at an elevation of 2000 ft. The variation of gust factors with height is thus established by the equation

$$F_z = F_{30}\left(\frac{30}{z}\right)^{0.0625} \qquad (3)$$

In Fig. 7 the adopted variation of gust factors with height is shown for comparison with the data taken on the 250-ft tower. It is seen that: (*a*) Such a curve is very nearly parallel to the lines plotted from Fig. 5 based on high 5-min average velocities and 5-sec gusts; (*b*) it gives an ample margin of safety for the usual gust factors found with the adopted 10-sec gusts; (*c*) it makes an allowance for the occasional appearance of the jets which were principally responsible for the high gust factors shown at El. 225; (*d*) it gives gust factors larger than those required for the 3-sec gusts that will be necessary to envelop buildings of less than 100 ft in height; and (*e*) for very large structures, which might require gusts of from 10 sec to 60 sec, there is an ample margin of safety.

DESIGN PRESSURE

The design pressure will always be equal to some shape factor multiplied by the velocity pressure. The ASCE Structural Division Committee on Wind

Forces is currently preparing recommendations regarding the velocity pressures to be used near the ground for different parts of the United States. Therefore, it seems reasonable to express the recommendation for the variation of design pressures with height in terms of those velocity pressures which are to be adopted for use near the ground in open, country. In this way, if the standard of reference is that which would prevail in open, level country, each designer can make whatever adjustments seem advisable to evaluate such influences as local shielding and unusual topography.

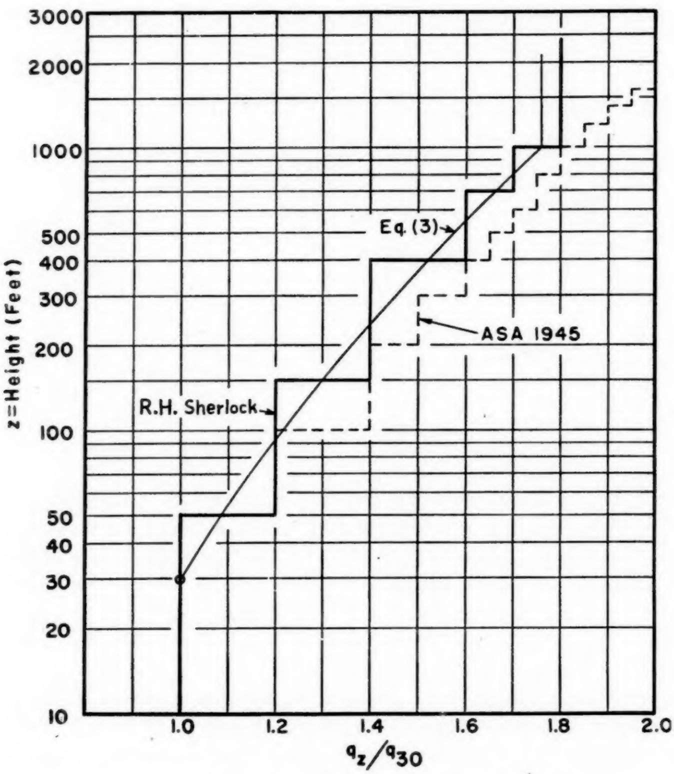


FIG. 10.—VARIATION OF DESIGN VELOCITY PRESSURE WITH HEIGHT

The relation between design pressure f, shape factor C, mass air density ρ, and wind velocity V is as follows (in pounds per square foot):

$$f = C\left(\frac{\rho V^2}{2}\right) = C\,q \qquad (4)$$

in which the velocity pressure q is expressed as:

$$q = \frac{\rho V^2}{2} \qquad (5)$$

If V_z and V_{30} are the maximum 5-min velocities at heights z and 30 ft, respectively, and if F_z and F_{30} are the corresponding gust factors:

$$\frac{q_z}{q_{30}} = \frac{\frac{1}{2}\rho V_1^2}{\frac{1}{2}\rho V_2^2} = \left(\frac{V_z F_z}{V_{30} F_{30}}\right)^2 = \left[\left(\frac{Z}{30}\right)^{1/7}\left(\frac{Z}{30}\right)^{-0.0625}\right]^2 = \left(\frac{Z}{30}\right)^{0.161} \quad (6)$$

Eq. 6 is valid up to $z = 1000$ ft, above which a constant value of q is to be used; that is:

$$q_z = q_{1000} \quad (7)$$

It will be seen that Eq. 6 includes the variation of both the velocity with height and the gust factor with height. It is represented in Fig. 10 by a curve, to which a stepped approximation is fitted as the recommendation of this paper

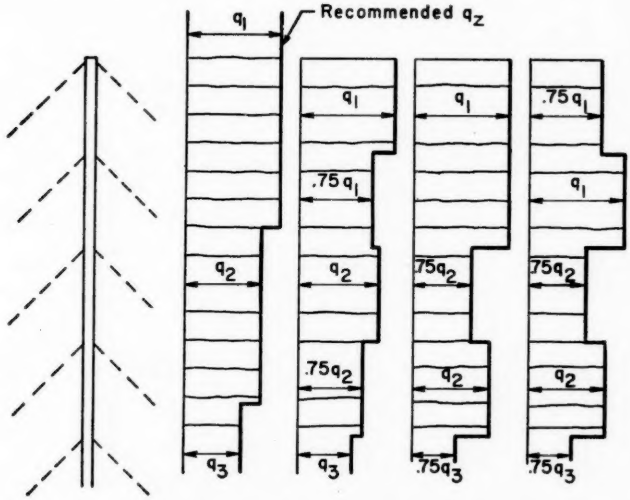


Fig. 11.—Wind Loading Variations to Produce Maximum Moments and Shears in a Guyed Tower

for the variation of velocity pressure with height. The stepped recommendations of the "American Standard Minimum Design Loads in Buildings and Other Structures" (ASA-A58.1–1945) are shown for comparison. The differences are chiefly that, in this paper (*a*) above 100 ft the velocity pressures are less; (*b*) fewer steps are used; and (*c*) a constant velocity pressure is used above 1000 ft.

Guyed Towers

Because of the presence of the jet type of gusts, and because the spans between the upper guys may be loaded with gusts that have not yet reached the lower spans, it is essential that deviations from the recommended variation of gust velocities with height should be taken into consideration in this type of structure. It is recommended that the velocity pressures shown in Fig. 10 should be reduced by 25% in that guyed span of a tower which would result in larger moments or shears in that span or any other span. This is shown dia-

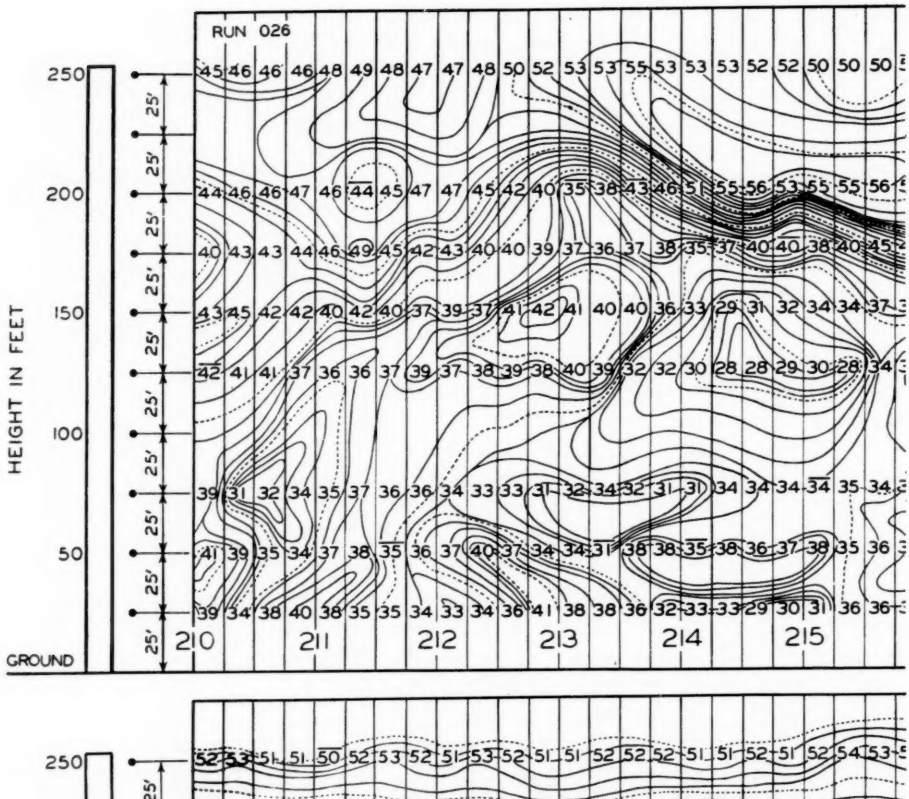
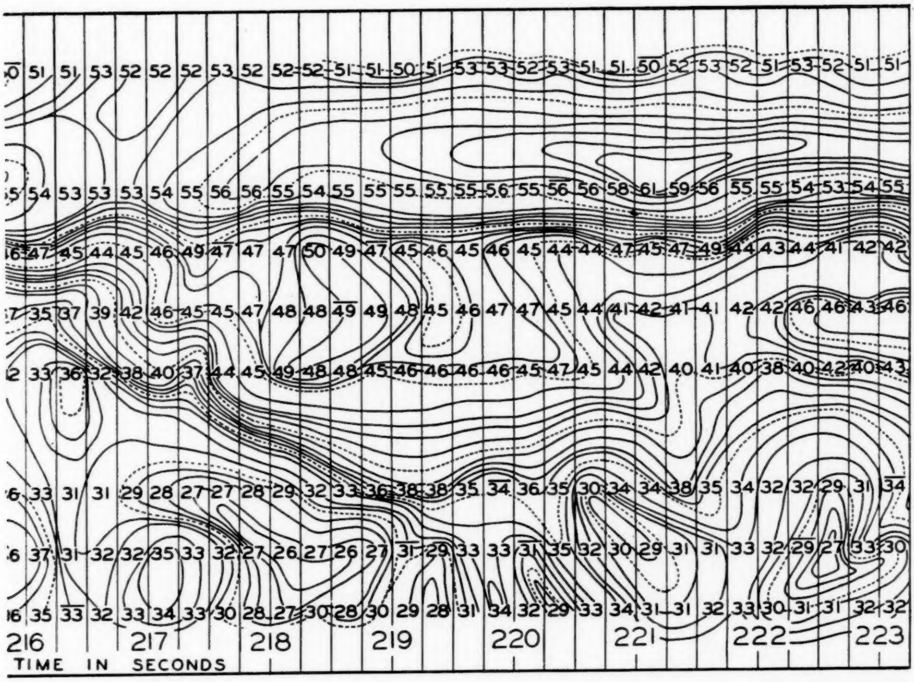


FIG. 12.—WIND MAP FOR PART OF RUN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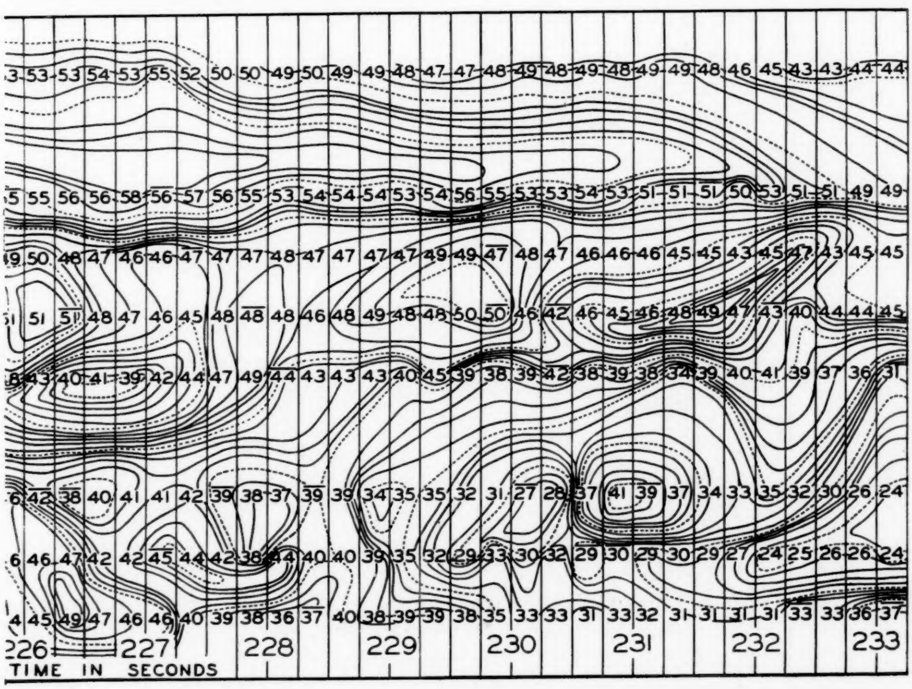
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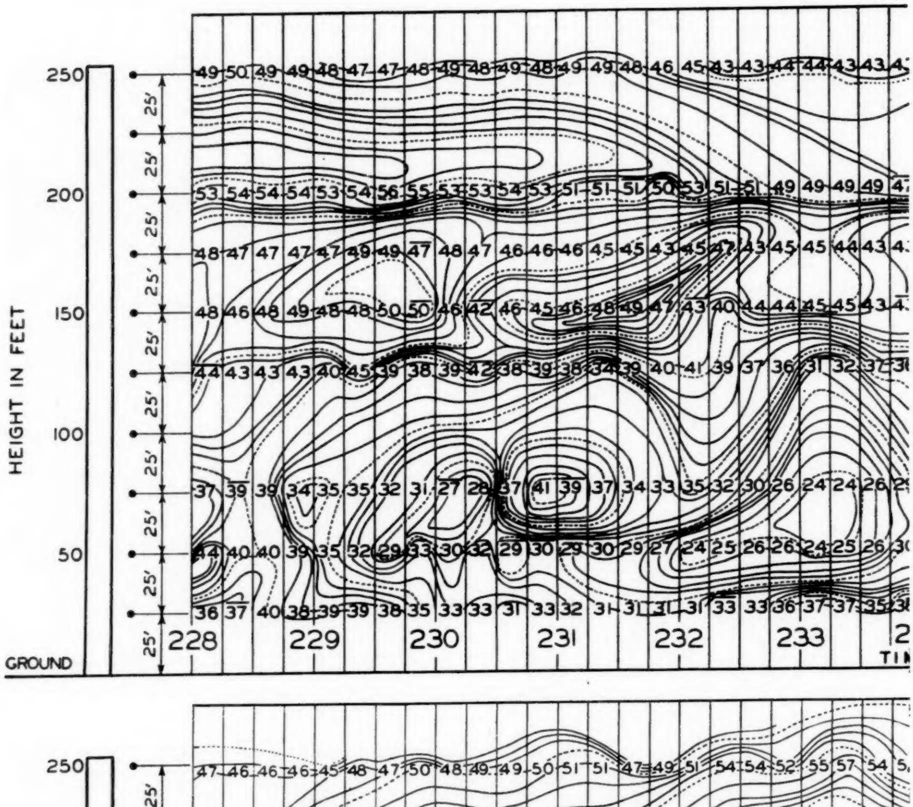
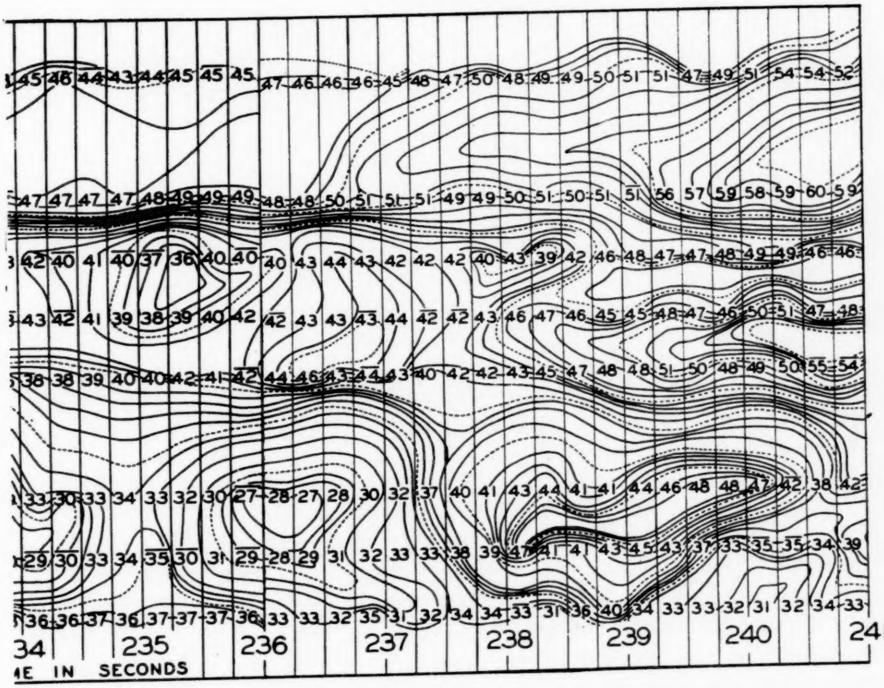


Fig. 12.—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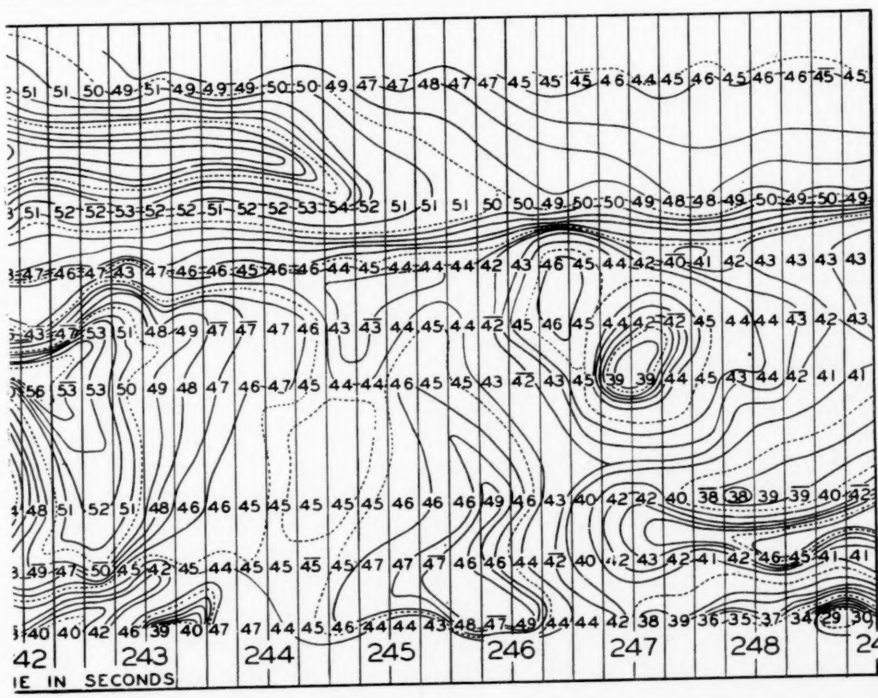
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grammatically in Fig. 11. It is based upon the study of vertical sections of the wind during passage of the jets, as shown in Fig. 12 and analyzed in Fig. 8.

Summary

The recommendations submitted in this paper involve the following basic considerations:

1. All recommendations should be based on conditions in open, level country as a standard of reference, and the influence of shielding and unusual topography should be evaluated by the designer in each individual case.
2. The effective ground—that is, the height in open, level country at which local disturbances are unimportant, and which approximates the height of anemometers now in use by the U. S. Weather Bureau in the first-order stations at airports—has been taken at 30 ft.
3. Recommendations should be based on velocity pressures and not on design pressures.
4. Shape factors should be taken into account separately.
5. The geographic distribution of maximum 5-min velocities near the ground should be taken from the U. S. Weather Bureau records. A gust factor of 1.5 at elevation 30 ft should be used in making the corresponding recommendation of velocity pressures near the ground.
6. The variation of air density with height should be ignored, since, on the average, it amounts to only about 3.3% in the first 1000 ft, and even this is subject to variations.
7. The equation for the relation between velocity and height should be based primarily on well-validated rational considerations rather than upon a statistical analysis of the nonhomogeneous U. S. Weather Bureau records.
8. The one-seventh power law is a sufficiently close approximation to the variation of wind velocity with height up to 1000 ft, above which a constant velocity is justified.
9. The variation of gust factors with height is adequately represented by Eq. 3.
10. The combined effect of the variation of maximum wind velocity with height and of maximum gust factors with height is given by Eq. 6.
11. Guyed towers should be designed for the moving-load effects of aerial jets and descending gust fronts.

Acknowledgment

This paper was written in connection with the writer's work on the ASCE Structural Division Committee on Wind Forces. It deals exclusively with the variation of the wind force as a function of the height above the ground. Other aspects of the action of the wind on engineering structures is being presented in a report of that committee.